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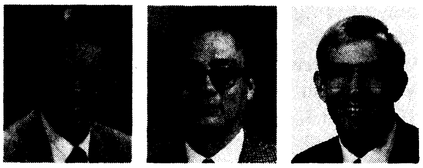
Strain-Rate Sensitive Behavior of Cement Paste and Mortar in Compression



by Shraddhakar Harsh, Zhenjia Shen, and David Darwin

The strain-rate sensitivity of the cement paste and mortar constituents of concrete is studied experimentally. Saturated cement paste and mortar specimens are loaded in compression to 15,000 microstrains, 27 to 29 days after casting, using strain rates ranging from 0.3 to 300,000 microstrains/sec. Water-cement ratios of 0.3, 0.4, and 0.5 are used. Strain-rate sensitivity of the materials is measured in terms of the initial elastic moduli, maximum stress, and corresponding strain. The initial elastic moduli and the strength of cement paste and mortar increase by 7 percent and 15 percent, respectively, with each order of magnitude increase in strain rate. The strain at the maximum stress is the greatest for the lowest strain rate. With an increase in strain rate, the strain at the maximum stress first decreases and then increases.

Keywords: cement pastes; compression; compressive strength; concretes; modulus of elasticity; **mortars (material);** Poisson ratio; sands; saturation; **strains;** stresses; stress-strain diagram.

The strain-rate sensitive behavior of concrete and its constituents has been under investigation for several decades.[1] The rate sensitivity has generally been measured in terms of the strength, modulus of elasticity, or the strain at the maximum stress in compression. It has also been measured in terms of Poisson's ratio, tensile strength, or flexural strength.

In most studies, the compressive strength of concrete and its constituents has been observed to increase approximately linearly with each order of magnitude (factor of 10) increase in strain rate, up to moderate strain rates, e.g., about 1000 microstrains/sec. Generally, the increase has been 7 to 15 percent with each order of magnitude increase in strain rate or stress rate.[1-8] In a few cases, however, the increase has been considerably less[9,10] or insignificant.[2,11] At higher than moderate strain rates (i.e., above 1000 microstrains/sec), there has been less agreement among various studies. Some have observed that the linear relation is maintained up to strain rates as high as 8×10^8 microstrains/sec,[12] while others have found the relation to be either concave upward,[10,13-15] or concave downward[16,17] with increasing strain rate.

The modulus of elasticity, while less sensitive than strength,[17-19] has also been found to increase with strain rate.

The effect of strain rate on the Poisson's ratio of oncrete has not been investigated extensively.[2,20] No results are available on the strain-rate sensitivity of Poisson's ratio for cement paste and mortar.

There is little agreement among researchers on the rate-sensitive behavior of the strain at the maximum stress. Some have found it to increase,[10,20,21] while others have found it to remain almost constant[19,22] or even decrease[2,17,23] with increasing strain rate. Generally, in cases when it was found to increase, the tests were done at higher strain rates.

In spite of the considerable number of studies on the rate sensitivity of concrete and its constituents, there are significant disagreements. The disagreements can sometimes be attributed to changes in test conditions, such as the moisture content of specimens, the curing conditions, or the range of strain rates used. For example, the insignificant increase in compressive strength with increasing strain rate observed by Dhir and Sangha[2] was most likely due to the low moisture content of their specimens, caused by storage in air for 10 weeks.

The purpose of this study is to help improve the knowledge of concrete by studying the rate-sensitive response of its constituents, cement paste, and mortar. The study is aimed at gathering basic information on the response of fully saturated materials, that is, materials that are not affected by drying. A study of materials in the saturated state, while not universally applicable to all concrete, directly applies to a large percentage of concrete structures, which remain saturated at depth. Compressive stress-strain response is measured in terms of the peak stress f_p, the strain corresponding to the peak stress ϵ_p, the initial modulus of

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elasticity E_i, and the initial Poisson's ratio ν_i. Material response is compared based on strain rate $\dot{\epsilon}$, water-cement ratio (w/c), and sand-cement ratio (s/c). Details of this study are provided in Reference 24.

RESEARCH SIGNIFICANCE

This experimental study investigates the strain-rate-sensitive behavior of saturated cement paste and mortar in compression. The stress-strain response of these materials is found to be significantly sensitive to the strain rate. The results indicate that the peak stress will increase with each order of magnitude increase in strain rate. The strain at peak stress first decreases, then increases with an increase in strain rate. The results clearly show that the initial elastic moduli of the materials also increase significantly with each order of magnitude increase in strain rate, which emphasizes how very few aspects of the response of these materials in compression can be considered independent of strain rate. This study has added significance because strain-rate tests are most often run on partially dried specimens (a complete lack of moisture control is not uncommon) and data from tests conducted under fully saturated conditions, as described in this paper, are sparse.

EXPERIMENTAL PROGRAM

Materials

Cement — Type I portland cement with the following composition was used: tricalcium silicate = 51.1 percent, dicalcium silicate = 22.3 percent, tetracalcium aluminoferrite = 9.5 percent, and tricalcium aluminate = 7 percent.

Fine aggregate — The fine aggregate was river sand consisting mainly of quartz, with 10 to 15 percent feldspar. Larger particles contained some limestone and dolomite. Fineness modulus = 2.91, bulk specific gravity (saturated surface dry) = 2.61, absorption = 0.79 percent. Source: Kansas River, Lawrence, Kansas. The sand was passed through a No. 4 sieve before use.

Mix proportions — Three water-cement ratios (w/c), 0.3, 0.4, and 0.5, were used for cement paste and mortar. Concrete mixtures were proportioned for each w/c to obtain the sand-cement ratio (s/c) for the corresponding mortar, designated as Mortar A. For w/c = 0.4 and 0.5, a second mortar, Mortar B, was also tested to evaluate the effect of a change in s/c upon the response. Mortar A with w/c = 0.3 had a s/c of 0.97. For w/c = 0.4, Mortar A had a s/c of 1.59, and Mortar B had a s/c of 1.97. For w/c = 0.5, Mortar A had a s/c of 2.28 and Mortar B had a s/c of 1.29.

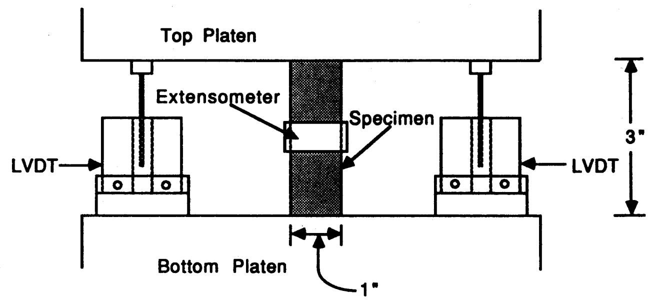

Fig. 1 — Schematic of test setup

Test specimens

Prismatic test specimens, 1 x 1 x 5 in., were prepared using steel molds. The constituents were mixed according to ASTM C 305-87,[25] except that the sand was oven-dried at 105 C for 24 hr and then presoaked for 5 min before mixing. The specimens were cast in a vertical position. The molds were filled in three equal layers. The degree of consolidation was adjusted to account for the stiffness of the plastic material. For w/c = 0.5, each layer was hand-rodded 25 times using a ¼-in. diameter steel rod. For w/c = 0.3 and 0.4, the molds were bolted to a vibrating table with a frequency of 60 cycles/sec and an amplitude of 0.006 in. Each layer was vibrated for 2.5 min for w/c = 0.3 and 2 min for w/c = 0.4. The molds were sealed at the top.

During the first 24 hr, the molds were stored in a horizontal position to reduce the effects of bleeding. The specimens were then removed from the molds and stored in lime-saturated water until the time of test.

Prior to testing, the specimens were shortened to 3 in. by removing equal portions from each end using a high-speed masonry saw. Each specimen was wrapped in plastic to avoid the loss of moisture. The specimens remained saturated throughout testing.

Loading procedure

Specimens were loaded in uniaxial compression using a closed-loop servo-hydraulic testing machine. A pair of linear variable differential transformers (LVDTs) were used to measure the average axial strain (Fig. 1), and to control the applied strain. The two LVDTs provided the average longitudinal strain for the total height of the specimen. Two extensometers were attached at midheight on opposite faces of the specimen to obtain the average lateral strain over the width of the specimen.

The specimens were strained in compression to 15,000 microstrain, insuring data from the descending as well as the ascending portions of the stress-strain

Table 1(a) — Summary of strain-rate tests

Strain rate (0-100%) $\mu\epsilon$/sec,* average (SD)†	Strain rate (5-20%) $\mu\epsilon$/sec,* average (SD)†	Strain rate (50-99%) $\mu\epsilon$/sec,* average (SD)†	No. of samples (No. of samples for ν_i)	Maximum stress, psi, average (SD)†	ϵ_p $\mu\epsilon$, average (SD)†	E_i psi $\times$ 10^6, average (SD)†	ν_i average (SD)†
Cement paste, w/c = 0.3							
0.30 (0)	0.30 (0)	0.30 (0)	2 (2)	11,675 (675)	9358 (2858)	2.94 (0.25)	‡ ‡
3.02 (0.02)	3.01 (0.032)	3.02 (0.02)	11 (10)	12,534 (464)	7450 (752)	3.396 (0.077)	0.212 (0.035)
30.4 (0.05)	30.3 (0.2)	30.3 (0)	2 (2)	14,061 (326)	7326 (755)	3.406 (0.073)	0.240 (0.016)
305 (1.00)	303 (3)	308 (2)	2 (2)	15,804 (326)	7036 (225)	3.649 (0.10)	0.247 (0.011)
3052 (32.4)	3181 (48.6)	3186 (432)	11 (11)	17,940 (617)	7037 (716)	3.792 (0.064)	0.270 (0.038)
31,662 (70)	40,221 (163)	31,009 (486)	2 (2)	21,989 (342)	8571 (220)	3.985 (0.013)	0.271 (0)
278,156 (11,239)	176,421 (7820)	402,344 (32,540)	11 (11)	22,876 (1313)	7960 (776)	4.206 (0.075)	0.262 (0.045)
Cement paste, w/c = 0.4							
0.30 (0)	0.30 (0)	0.30 (0)	2 (2)	7456 (80)	10,703 (491)	2.256 (0.001)	0.218 (0.024)
3.05 (0.02)	3.04 (0.05)	3.05 (0.02)	2 (4)	7755 (19)	7007 (772)	2.494 (0.005)	0.227 (0.019)
30.5 (0.05)	30.8 (0.2)	30.5 (0.05)	2 (4)	8502 (71)	6377 (63)	2.65 (0.049)	0.245 (0.025)
304 (1)	298.6 (4.9)	304 (1.4)	2 (4)	9544 (227)	6494 (358)	2.777 (0.005)	0.256 (0.033)
3072 (2)	3270 (0)	3041 (7)	2 (4)	10,557 (235)	6501 (391)	2.752 (0.016)	0.247 (0.029)
32,248 (117)	38,718 (113)	30,897 (68)	2 (4)	11,956 (19)	6597 (427)	2.862 (0.016)	0.269 (0.028)
282,410 (3515)	161,384 (864)	398,143 (9634)	2 (4)	13,406 (106)	6533 (205)	3.135 (0.001)	0.273 (0.019)

*Microstrains/sec.
† Standard deviation.
‡ Data not obtained.

curve at all strain rates. The specimens were loaded at seven strain rates, ranging from 0.3 microstrain/sec (3.0×10^{-7}/sec) to over 300,000 microstrains/sec (3.0×10^{-1}/sec). Successive strain rates were separated by a factor of 10 (one order of magnitude). At the slowest strain rate, specimens failed in about 12 hr, while at the fastest strain rate they failed in 0.03 sec. These strain rates and test durations can be compared to those for typical compression tests for concrete, which are made at a strain rate of about 15 microstrains/sec and last about 2 min. The highest strain rates used are comparable to strain rates that occur in a helicopter crash.[26]

In the data that follow, three strain rates are shown: the average strain rate from zero stress to the peak stress $\dot{\epsilon}_{0\text{-}100}$, the average strain rate from 5 to 20 percent of the peak stress $\dot{\epsilon}_{5\text{-}20}$, and the average strain rate from 50 percent of the peak stress to the point on the descending portion of the stress-strain curve where the stress equals 99 percent of the peak stress $\dot{\epsilon}_{50\text{-}99}$. While $\dot{\epsilon}_{5\text{-}20}$ controls the initial response of the materials, $\dot{\epsilon}_{50\text{-}99}$ appears to control the response near the peak stress.

Table 1 (a) through (d) shows the average results for cement paste and mortar specimens including strain rates, number of specimens, peak stress, strain at peak stress, initial modulus of elasticity, and initial Poisson's ratio.

EXPERIMENTAL RESULTS AND DISCUSSION

Failure mode

As the strain rate increased, specimens failed more abruptly, with an increasing number of cracks and a louder cracking noise. This behavior was most evident for the cement paste with lowest water-cement ratio. At the highest strain rate, in excess of 300,000 microstrains/sec, cement paste specimens with w/c = 0.3 disintegrated into a large number of fragments, which frequently flew out of the plastic cover. Mortar specimens, especially those with high water-cement ratios, failed with comparatively less violence. At higher strain rates, mortar specimens generated particles of sand and paste in the failure regions. The failure cracks in cement paste were generally straighter, longer, and cleaner than those in the mortar specimens. At higher strain rates, cracks were larger in number and straighter, and the specimens produced a larger number of fragments at failure than at lower strain rates. The sensitivity of the failure mode of concrete specimens to strain rate has been observed by others.[16,22]

Table 1(b) — Summary of strain-rate tests

Strain rate (0-100%) $\mu\epsilon$/sec,* average (SD)†	Strain rate (5-20%) $\mu\epsilon$/sec,* average (SD)†	Strain rate (50-99%) $\mu\epsilon$/sec,* average (SD)†	No. of samples (No. of samples for ν_i)	Maximum stress, psi, average (SD)†	ϵ_p $\mu\epsilon$, average (SD)†	E_i psi $\times 10^6$ average (SD)†	ν_i average (SD)†
Cement paste, w/c = 0.5							
0.30 (0)	0.31 (0)	0.30 (0)	2 (3)	5048 (79)	7024 (632)	1.760 (0.034)	0.218 (0.0)
3.0 (0.02)	3.01 (0.029)	3.0 (0.02)	11 (3)	5896 (318)	6311 (737)	2.035 (0.097)	0.234 (0.007)
30.4 (0.05)	30.5 (0.20)	30.4 (0.05)	2 (2)	6551 (38)	5857 (27)	1.935 (0.032)	0.214 (0.017)
305 (2)	298.8 (1)	305 (2)	2 (2)	6897 (31)	5358 (262)	2.114 (0.010)	0.247 (0.030)
3048 (20)	3330 (66.7)	3007 (21.9)	11 (0)	7878 (398)	5568 (638)	2.339 (0.086)	0.267 (0.021)
32,863 (167)	38,002 (12)	31,160 (191)	2 (2)	8093 (211)	5198 (261)	2.289 (0.037)	0.261 (0.024)
284,722 (8700)	162,043 (6064)	391,875 (10,801)	11 (0)	9816 (629)	5886 (552)	2.678 (0.103)	0.281 (0.012)
Mortar, w/c = 0.3, s/c = 0.97							
0.30 (0)	0.30 (0.005)	0.30 (0)	2 (0)	9831 (155)	4901 (100)	3.843 (0.386)	‡ ‡
3.04 (0)	2.99 (0.03)	3.05 (0.01)	2 (1)	10,841 (23)	4157 (55)	4.553 (0.045)	0.207 (0.0)
30.3 (0)	30.5 (0.025)	30.3 (0.5)	2 (2)	12,323 (215)	4164 (56)	4.906 (0.059)	0.235 (0.0)
291 (13)	306 (3)	302 (0)	2 (2)	13,394 (212)	4183 (37)	5.070 (0.067)	0.236 (0.021)
3090 (10)	3681 (136)	3068 (12)	2 (2)	14,558 (167)	4226 (185)	5.008 (0.097)	0.238 (0.031)
32,155 (914)	29,730 (2132)	31,447 (595)	2 (2)	15,695 (196)	4377 (94)	5.955 (0.716)	0.260 (0.014)
264,352 (7939)	141,982 (10014)	465,254 (2666)	2 (2)	17,804 (240)	4636 (33)	5.675 (0.211)	0.274 (0.020)

*Microstrains/sec.
† Standard deviation.
‡ Data not obtained.

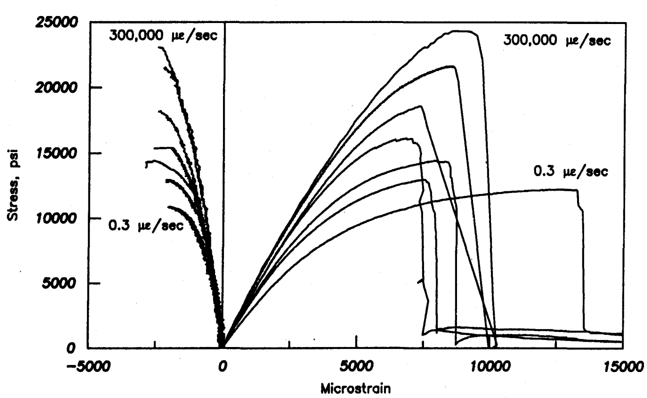

Fig. 2 — Stress versus longitudinal and transverse strain for cement paste with w/c *= 0.3, tested at strain rates from 0.3 to 300,000 microstrains/sec*

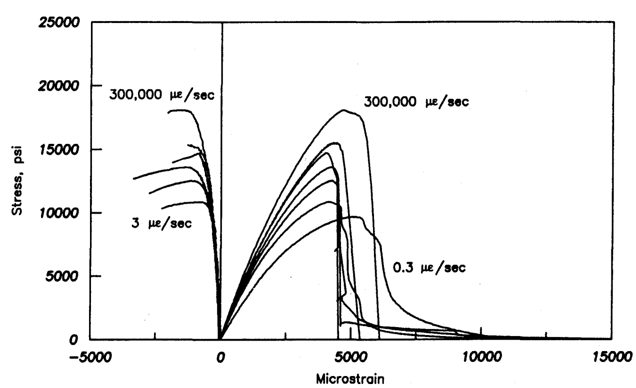

Fig. 3 — Stress versus longitudinal and transverse strain for mortar with w/c *= 0.3, tested at strain rates from 0.3 to 300,000 microstrains/sec*

Stress-strain curves

Fig. 2 and 3 show typical stress-strain curves at the seven strain rates for cement paste and mortar with w/c = 0.3. Oscillations after the peak stress in the stress-strain curves at higher strain rates are due to the limited stiffness of the load frame and the finite response time of the servo-hydraulic feedback system. The figures show both the longitudinal and transverse strains. Similar curves were also obtained for w/c = 0.4 and 0.5.[24]

A significant change in the stress-strain response of the materials with each order of magnitude increase in

Table 1(c) — Summary of strain-rate tests

Strain rate (0-100%) $\mu\epsilon$/sec,* average (SD)†	Strain rate (5-20%) $\mu\epsilon$/sec,* average (SD)†	Strain rate (50-99%) $\mu\epsilon$/sec,* average (SD)†	No. of samples (No. of samples for ν_i)	Maximum stress, psi, average (SD)†	ϵ_p $\mu\epsilon$, average (SD)†	E_i psi × 10^6 average (SD)†	ν_i, average (SD)†
Mortar A, w/c = 0.4, s/c = 1.59							
0.31 (0)	0.30 (0)	0.30 (0)	2 (0)	7356 (39)	4132 (61)	3.898 (0.10)	‡ ‡
3.03 (0.03)	3.01 (0.38)	3.03 (0.04)	2 (0)	7814 (60)	3712 (72)	4.256 (0.046)	‡ ‡
30.6 (0.5)	30.4 (0.38)	30.6 (0.01)	2 (1)	8812 (92)	3336 (196)	4.738 (0.176)	0.205 (0.0)
306 (0.5)	293 (7)	306 (0.1)	2 (2)	9588 (184)	3502 (32)	4.978 (0.079)	0.256 (0.017)
3038 (84)	3970 (56)	3080 (30)	2 (1)	10,398 (180)	3520 (225)	4.938 (0.315)	0.269 (0.001)
32,262 (551)	26,135 (515)	31,776 (551)	2 (2)	11,278 (148)	3721 (133)	5.100 (0.141)	0.273 (0.001)
267,708 (4935)	126,581 (4219)	521,089 (29,090)	3 (2)	12,547 (116)	3620 (180)	5.817 (0.189)	0.281 (0.011)
Mortar B, w/c = 0.4, s/c = 1.97							
0.31	0.30	0.30	1 (0)	7566	4045	3.888	‡
3.04 (0.02)	3.01 (0.05)	3.03 (0.027)	5 (2)	8002 (178)	3272 (151)	4.618 (0.212)	0.228 (0.027)
30.6 (0.05)	30.2 (0.4)	30.4 (0.1)	2 (2)	8760 (57)	3200 (10)	4.851 (0.073)	0.249 (0.022)
304 (1)	297 (3.5)	303 (1)	2 (1)	9724 (87)	3267 (122)	5.195 (0.132)	0.270 (0.0)
3111 (22)	3915 (0)	3047 (16)	2 (2)	10,508 (52)	3142 (109)	5.450 (0.009)	0.278 (0.006)
32,345 (1057)	28,965 (3489)	31,692 (1127)	3 (1)	11,515 (58)	3398 (76)	5.689 (0.211)	0.273 (0.0)
264,199 (3785)	123,744 (489)	512,384 (15476)	2 (0)	12,720 (213)	3568 (146)	5.954 (0.024)	‡

* Microstrains/sec.
† Standard deviation.
‡ Data not obtained.

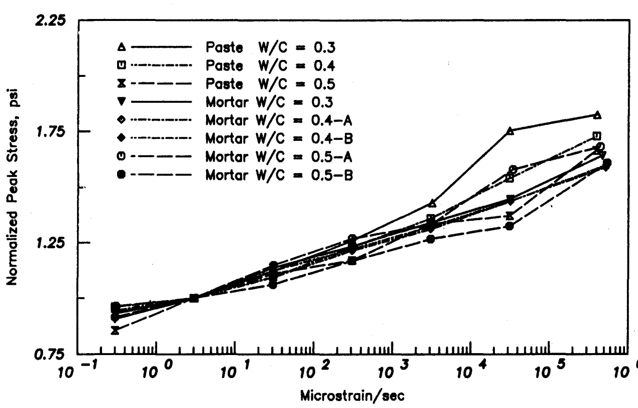

Fig. 4 — Normalized peak stress versus strain rates ($\dot{\epsilon}_{5\text{-}20}$) for cement paste and mortar with w/c *= 0.3, 0.4, and 0.5*

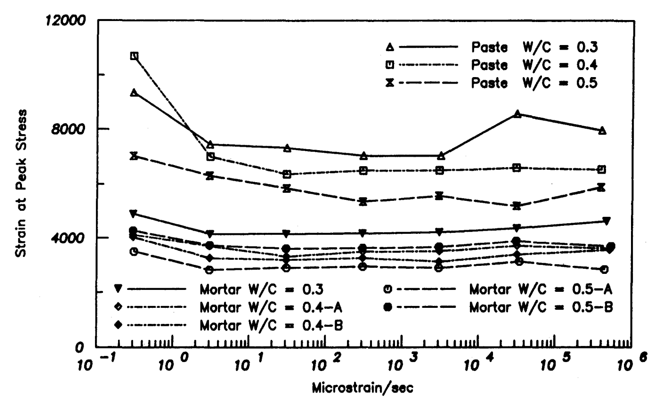

Fig. 5 — Strain at the peak stress versus strain rate ($\dot{\epsilon}_{50\text{-}99}$) for cement paste and mortar with w/c *= 0.3, 0.4, and 0.5*

strain rate is clearly seen in these figures. For each material, as the strain rate is increased, both the initial slope and the peak stress increase, while the nonlinearity of the initial response decreases. The strain at the peak stress is generally the greatest at the lowest strain rate (0.3 microstrain/sec). As the strain rate is increased, the strain at the peak stress first decreases and then increases. Similar variations have been observed by others[2,17,27,28] for concrete and its constituents. Specific aspects of the response of the materials as a function of strain rate are discussed next.

Peak stress

Fig. 4 shows the normalized peak stress of each material as a function of strain rate $\dot{\epsilon}_{50\text{-}99}$ and represents all specimens summarized in Table 1. The peak stresses are normalized by dividing the average peak stress at each strain rate by the average peak stress obtained at 3 mi-

Table 1(d) — Summary of strain-rate tests

Strain rate (0.100%) $\mu\epsilon$/sec,* average (SD)†	Strain rate (5-20%) $\mu\epsilon$/sec,* average (SD)†	Strain rate (50-99%) $\mu\epsilon$/sec,* average (SD)†	No. of samples (No. of samples for ν_i)	Maximum stress, psi, average (SD)†	ϵ_p $\mu\epsilon$, average (SD)†	E_i psi × 10^6 average (SD)†	ν_i, verage (SD)†
Mortar A, w/c = 0.5, s/c = 2.28							
0.31	0.30	0.31	3 (0)	5379 (65)	3503 (434)	3.490 (0.184)	‡
3.01 (0.02)	2.98 (0.09)	3.01 (0.03)	12 (2)	5582 (279)	2827 (185)	4.024 (0.163)	0.190 (0.004)
30.4 (0.08)	30.1 (0.24)	30.5 (0.08)	3 (2)	6407 (122)	2908 (108)	4.147 (0.103)	0.210 (0.031)
307 (0.81)	293 (1)	305 (1.63)	3 (2)	7090 (70)	2948 (46)	4.561 (0.055)	0.218 (0.031)
3089 (28)	4211 (259)	3017 (22)	12 (2)	7434 (270)	2907 (180)	4.584 (0.149)	0.227 (0.004)
34,645 (210)	27,487 (775)	34,071 (297)	3 (2)	8824 (266)	3135 (125)	5.050 (0.161)	0.248 (0.0)
21,9728 (15,162)	97,292 (6318)	438,418 (29,980)	12 (0)	9391 (585)	2839 (156)	5.451 (0.177)	‡
Mortar B, w/c = 0.5, s/c = 1.29							
0.30 (0)	0.31 (0.1)	0.30 (0)	2 (0)	5712 (49)	4284 (0)	3.020 (0.258)	‡
3.03 (0.01)	2.96 (0.03)	3.03 (0.01)	5 (4)	6240 (140)	3745 (200)	3.500 (0.111)	0.199 (0.019)
30.3 (0)	29.8 (0)	30.3 (0.1)	2 (1)	6626 (54)	3626 (27)	3.690 (0.031)	0.224 (0.0)
304 (0.5)	298 (5)	302 (0.5)	2 (2)	7297 (12)	3637 (115)	3.923 0.121	0.231 (0.051)
3078 (5)	3580 (41)	3038 (24)	2 (2)	7908 (80)	3680 (39)	3.952 (0.110)	0.232 (0.008)
32,637 (1081)	34,218 (582)	30,982 (1037)	2 (2)	8273 (136)	3900 (31)	3.714 (0.200)	0.251 (0.023)
293,825 (8464)	137,452 (8165)	532,744 (3105)	2 (2)	10,040 (330)	3699 (33)	4.891 (0.181)	0.267 (0.006)

*Microstrains/sec.
†Standard deviation.
‡Data not obtained.

crostrains/sec. Fig. 4 indicates that with every order of magnitude increase in strain rate, the strength of saturated cement paste and mortar increases about 15 percent. This nearly linear increase in strength with each order of magnitude increase in strain rate does not appear to be a function of the type of material (paste or mortar) or the water-cement ratio, although the two highest strength pastes show the greatest increase in strength at the highest strain rate (it is not clear whether this is a true trend or just statistical scatter).

The fact that the effects of strain rate on strength are virtually the same for the materials tested indicates that the mechanisms that control the rate-sensitive behavior of these materials are quite similar.

Strain at peak stress

Fig. 5 shows the variation in the average strain at the peak stress ϵ_p, as a function of strain rate ($\dot{\epsilon}_{50\text{-}99}$) for cement paste and mortar. For both materials, the nonmonotonic variation in ϵ_p is clearly shown in Fig. 5. ϵ_p first decreases and then increases with increasing strain rate. In each case, the slowest test rate (test duration = 12 hr) results in the highest value of ϵ_p, due to the effect of creep. As the strain rate increases, the creep effects decrease and ϵ_p decreases accordingly. With a further increase in strain rate, ϵ_p once again increases. This increase in ϵ_p is likely the result of limitations in crack velocity compared to the rate of loading.

Initial modulus of elasticity

In this study, the initial modulus of elasticity E_i is taken as the slope of the best fit line through the stress-strain curve between 5 and 20 percent of the peak stress. This range is selected to remove the initial seating errors as a specimen is loaded, to allow a range wide enough to limit the effects of scatter, and to keep the upper limit at a value where the response is virtually linear (i.e., not significantly effected by microcracking). Like the peak stress, normalized values of E_i are obtained by dividing the values at various strain rates by the value at 3 microstrains/sec. Fig. 6 shows the change in the normalized values of E_i of each material as a function of strain rate $\dot{\epsilon}_{5\text{-}20}$. As with strength, E_i increases approximately linearly with each order of magnitude increase in strain rate. However, the increase is only about half of the corresponding percentage increase in strength. The lower rate sensitivity of E_i compared to strength is consistent with similar obser-

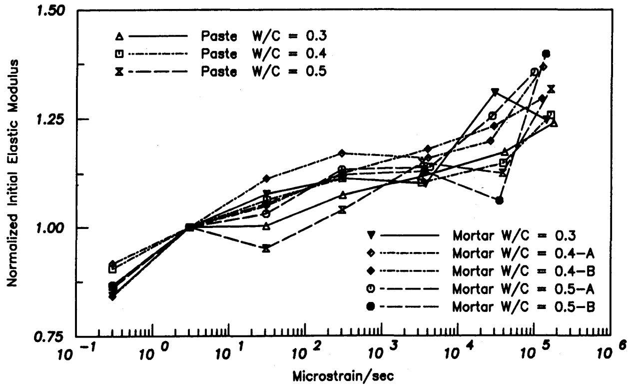

Fig. 6 — Normalized initial modulus of elasticity versus strain rate ($\dot{\epsilon}_{5\text{-}20}$) for cement paste and mortar with w/c = *0.3, 0.4, and 0.5*

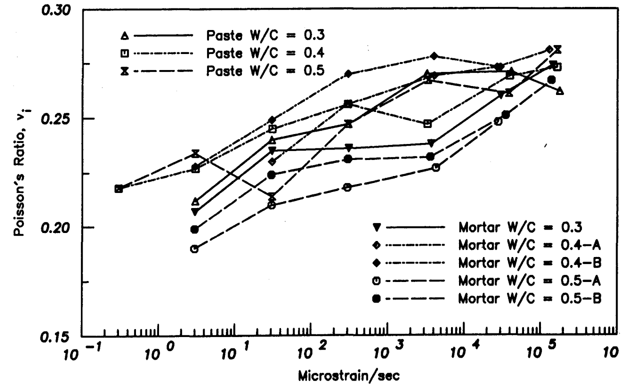

Fig. 7 — Initial Poisson's ratio versus strain rate ($\dot{\epsilon}_{5\text{-}20}$) for cement paste and mortar with w/c = *0.3, 0.4, and 0.5*

vations in studies of concrete.[17-19] For both cement paste and mortar, E_i increases by about 7 percent for each order of magnitude increase in strain rate as the strain rate $\dot{\epsilon}_{5\text{-}20}$ increases from 0.3 microstrain/sec to about 150,000 microstrains/sec.

Initial Poisson's ratio

Fig. 7 illustrates the variation in the average initial Poisson's ratios of the pastes and mortars as a function of strain rate ($\dot{\epsilon}_{5\text{-}20}$). The initial Poisson's ratio μ_i illustrated here is calculated at 20 percent of the strength. The data points shown represent the average values listed in Table 1. The values fall within a relatively narrow range, with μ_i being, on the average, somewhat lower for mortar than for cement paste. For example, at $\dot{\epsilon}_{5\text{-}20}$ of 3, 3000, and 150,000 microstrains/sec, the ranges in μ_i are 0.199 to 0.234, 0.227 to 0.270, and 0.262 to 0.281, respectively. The strain-rate sensitivity of the initial Poisson's ratio is about the same as that of the initial modulus of elasticity, about 7 percent for each order magnitude increase in strain rate.

The magnitude of the increase in μ_i is consistent with the observations of Dhir and Sangha[2] for concrete. Strain-rate sensitivity of the Poisson's ratio at higher strain levels is discussed in Reference 24.

While the rate sensitivity of stress-strain response near failure can be related to the initiation and growth of cracks,[24,29-31] the same cannot be said for the rate sensitivity of the initial moduli E_i and μ_i. Very little cracking occurs at the strain levels at which E_i and μ_i are calculated,[32-34] yet these parameters are significantly rate sensitive, indicating that another mechanism, in all likelihood moisture movement, plays an important role in the initial response of the materials. The importance of moisture movement in controlling material stiffness at low stresses is discussed in detail in Reference 24.

The sensitivity of E_i and μ_i to strain rate also points out that these properties are not in themselves basic properties of the materials, but rather that they depend on other material characteristics, such as porosity and degree of saturation, which control stress-strain behavior.[24]

Effect of sand content

Sand increases the initial modulus of elasticity and reduces the strength and ductility of mortar in comparison to cement paste. As discussed by Attiogbe and Darwin,[32] sand acts as a stress raiser, thus increasing the local compressive and lateral tensile stresses within the material. The increase in local stresses reduces both the strength and the strain capacity of the composite materials compared to paste. As Table 1 shows, the strain at the peak stress ϵ_p is lower for mortar than for cement paste with the same water-cement ratio. Also, between the two mortars at a given water-cement ratio, the mortar with the higher sand-cement ratio has the lower ϵ_p. The addition of relatively stiffer sand particles to cement paste increases the initial stiffness. Thus, mortars have higher initial elastic moduli than pastes with the same water-cement ratio. At a given water-cement ratio, the mortar with the higher sand content (Mortar B for w/c = 0.4 and Mortar A for w/c = 0.5) has a higher initial elastic modulus than the mortar with the lower sand content.

The effects of strain rate on the strength and initial elastic moduli of both cement paste and mortar appear to be about the same, indicating that the controlling mechanisms are not greatly affected by either the water-cement ratio or sand content.

The comparisons of the previous sections show that the rate sensitivities of the stress-strain behavior near failure, the initial modulus of elasticity, and the initial Poisson's ratio do not change with strength. Thus the results differ from previous observations for concrete in which weaker concrete was observed to be more rate sensitive than stronger concrete.[3,8,16,22,31,35]

The key reason for the conflict is that the earlier studies that cite the greater relative strength enhancement of lower strength concrete with increasing loading rate were performed under stress control or at "constant loading head speed" rather than strain control. In either case, the strain rate will increase more near the peak stress for weaker concretes than for stronger concretes. Thus the weaker materials were really subjected to a higher strain rate and should be expected to show more strength enhancement than stronger materials.

CONCLUSIONS

The following conclusions are drawn from the test results and discussion presented in this paper. The materials represent the cement paste and mortar constituents of concrete, in a fully saturated condition, loaded at strain rates ranging from 0.3 to 300,000 microstrains/sec.

1. The stress-strain curves of cement paste and mortar are nonlinear up to a nominal strain rate of 300,000 microstrains/sec.

2. The nonlinearity of the stress-strain curves for cement paste and mortar decreases with increasing strain rate.

3. The compressive strength, initial modulus of elasticity, and initial Poisson's ratio of cement paste and mortar increase approximately linearly with each order of magnitude increase in strain rate. Strength increases about 15 percent with each order of magnitude increase in strain rate, while the initial elastic moduli increase about 7 percent.

4. The relative increases in strength, initial modulus of elasticity, and Poisson's ratio with strain rate are about the same for cement paste and mortar, independent of water-cement ratio and sand-cement ratio.

5. The strain at the peak stress varies in a nonmonotonic manner with strain rate. Its value is greatest at the slowest strain rate, 0.3 microstrain/sec. With increasing strain rate, it first decreases then increases.

6. The introduction of sand lowers the strain capacity of cement paste. At a given water-cement ratio, cement paste has a higher strain at the peak stress than does mortar. For mortars, the lower the sand content, the higher strain at the peak stress.

7. The introduction of sand increases the initial modulus of elasticity of cement paste. Within the ranges considered, the higher the sand content, the higher the initial modulus of elasticity.

8. The initial moduli are not themselves basic properties of the materials, but they depend upon other material characteristics. The strain-rate sensitivity of the initial moduli at strains where very little cracking is expected, strongly indicates the importance of moisture movement.

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